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A METHODOLOGICAL INVESTIGATION OF THE COSTS OF CARBON SEQUESTRATION

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I. Introduction

Increased attention by policy makers to the threat of global climate change has brought with it considerable attention to the possibility of encouraging the growth of forests as a means of sequestering carbon dioxide (National Academy of Sciences 1992; Intergovernmental Panel on Climate Change 1994).[1] This approach has, in fact, become an explicit element of both U.S. and international climate policies (U.S. Department of Energy 1991; Clinton

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[1]After fossil-fuel combustion, deforestation is the second largest source of carbon dioxide emissions to the atmosphere. There are three pathways along which carbon sequestration is of relevance for atmospheric concentrations of carbon dioxide: carbon storage in biological ecosystems; carbon storage in durable wood products; and substitution of biomass fuels for fossil fuels (Richards and Stokes 95). The model developed in this paper considers the first two pathways.

and Gore 1993; United Nations General Assembly 1992). This high level of interest has been due, in part, to: suggestions that sufficient lands are available to use the approach to mitigate a substantial share of annual carbon dioxide (CO_2) emissions (Marland 1988; Lashof and Tirpak 1989; and Trexler 1991); and claims that growing trees to sequester carbon is a relatively inexpensive means of combating climate change (Dudek and LeBlanc 1990; National Academy of Sciences 1992; Sedjo and Solomon 1989). In other words, the serious attention given by policy makers to carbon sequestration can partly be explained by (implicit) assertions about respective marginal cost functions.

This paper develops a methodology whereby estimates of the costs of carbon sequestration can be developed on the basis of evidence from observations of landowners' behavior when confronted with the opportunity costs of alternative land uses. The analytical model takes account of silvicultural understanding of the intertemporal linkages between deforestation and carbon emissions, on the one hand, and between forestation and carbon sequestration, on the other. The results support the efficacy and potential value of this analytical approach.

The simplest economic analyses of the costs of carbon sequestration have derived single point estimates of average costs associated with particular sequestration levels (Marland 1988; Sedjo and Solomon 1989; Dudek and LeBlanc 1990; Rubin, *et.al.* 1992; Masera, Bellon, and Segura 1995). In a number of cases, it has been assumed, implicitly or explicitly, that land (opportunity) costs are zero (Dixon, *et.al.* 1994; New York State Energy Office 1993; Winjum, Dixon, and Schroeder 1992; Van Kooten, Arthur, and Wilson 1992). Another set of studies —essentially «engineering/costing models» — have constructed marginal cost schedules by adopting land rental rates or purchase costs derived from surveys for representative types or locations of land, and then sorting these in ascending order of cost (Moulton and Richards 1990; Richards, Moulton, and Birdsey 1993). Simulations models include a model of the lost profits due to removing land from agricultural production (Parks and Hardie 1995), a mathematical programming model of the agricultural sector and the timber market used to estimate the loss of consumer surplus from food price increases due to reduction of agricultural land availability (Adams, *et.al.* 1993), a related model incorporating the effects of agricultural price support programs (Callaway and McCarl 1996), and a dynamic simulation model of forestry (Swinehart 1996). Lastly, an analysis by Plantinga (1995) adopts land-use elasticities from an econometric study to estimate sequestration costs in southwestern Wisconsin.

Each of these previous analyses has its own comparative advantages, and a number of the studies have absolute advantages along particular dimensions. The research described in the current paper draws on some of the best features of each, including the carbon levelization method of Adams *et.al.* (1993) and Moulton and Richards (1990), and the intertemporal carbon yield curves of Richards, Moulton, and Birdsey (1993). Nearly all of the previous analyses are potentially limited, however, by their inability to reflect the actual preferences of landowners, as revealed — for example — by landowners' decisions regarding the disposition of their lands in the face of relevant economic signals.[2] One aspect of this problem has been described by Richards, Moulton, and Birdsey (1993, pp. 911-912) as follows:

> One of the difficulties in conducting an engineering or «least cost» type of analysis is that it assumes that 100 percent of the marginal agricultural land is available for conversion to tree plantations. In fact, that level of participation by agricultural land owners is not likely in the absence of the exercise of eminent domain or public taking powers.

In the words of these same researchers, there has been an observed «tendency of some land owners to hang on to their land longer or more stubbornly» (p. 912) than the simplest economic calculations would suggest.

There are a number of reasons why landowners' actual behavior might not be well predicted by «engineering» or «least cost» analyses: (1) land-use

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[2]The exception is the analysis by Plantinga (1995), which is similar in some respects to the methodology developed in this paper.

changes can involve irreversible investments in the face of uncertainty (Parks 1995), and so option values — ignored in engineering and least-cost analyses — may be important (Pindyck 1991); (2) there may be non-pecuniary returns to landowners from forest uses of land (Plantinga 1995), as well as from agricultural uses; (3) liquidity constraints or simple «decision-making inertia» may mean that economic incentives will affect landowners only with some delay; and (4) there may be private, market benefits or costs of alternative land uses (or of changes from one use to another) of which the analyst is unaware.

We seek to address these problems by employing an econometric model of actual land-use behavior to derive the costs of carbon sequestration. Thus, the paper is intended to be illustrative of how existing econometric analyses of land use, which already exist for a number of countries, can be used to develop better region-specific estimates of the marginal costs of carbon sequestration.

In Part II, we describe the analytical model, including a brief summary of the structural model of historical land use that is drawn from a previous analysis, the dynamic simulation model of future land use, and the related simulation model of carbon sequestration. In Part III, we describe the results of simulations that facilitate the derivation of estimates of the marginal costs of carbon sequestration. In Part IV, we conclude with some observations on potential future applications.

II. Analytical Model

We draw upon econometrically-estimated parameters of a structural model of land use, and layer upon it a model of the relationships that link changes in alternative land uses with changes in the time paths of CO_2 emission and sequestration. The major steps in the analysis are as follows. First, a dynamic optimization model of individual landowner decision making is solved with basic control-theoretic techniques. The model focuses on the empirically relevant land-use options of forest and farm.[3] By allowing for unobserved heterogeneity of land quality, the individual necessary conditions from that optimization model are aggregated into an econometric specification, the parameters of which are estimated with available aggregate time-series and cross-sectional data. These results provide the first building block for the model of carbon sequestration.

The estimated econometric model indicates how land use may be anticipated to change in response to changes in the economic climate, including such relevant factors as expected timber and agricultural product prices, and costs of changing land use. Hence, a properly specified and related simulation model can produce fitted values of land use changes that would take place in response to government policies such as taxes on deforestation or subsidies on forestation. Such simulations yield, in effect, a forest supply function.

Next, a set of models of the various relationships that exist between the time path of deforestation and carbon emissions and the time path of forestation and carbon sequestration are linked with the land-use model, so that we can predict net carbon emissions/sequestration associated with a given tax/subsidy and a given set of background economic variables. Finally, the simulation model is modified so that its results are expressed in terms of marginal costs of carbon sequestration and total annual sequestration. This provides estimates of the key statistic: the incremental costs of sequestration.

A. A Structural, Empirical Model of Land Use

In previous work with a distinctly different policy motivation, a dynamic optimization model was developed of a landowner's decision of whether to keep his or her land in its status quo use or convert it to serve another

[3] In both industrialized nations and in developing countries, nearly all deforestation is associated with conversion to agricultural use (Jepma, Asaduzzaman, Mintzer, Maya, and Al-Moneef 1995).

purpose.[4] Landowners are assumed to observe current and past values of economic, hydrologic, and climatic factors relevant to decisions regarding the use of their lands for forestry or agricultural production,[5] and on this basis form expectations of future values of respective variables. In particular, landowners observe agricultural prices and production costs, typical agricultural yields for their area, typical timber returns, and the suitability of individual land parcels for agriculture.

Landowners are assumed to attempt to maximize the expected long-term economic return to the set of productive activities that can be carried out on their land. They face ongoing decisions of whether to keep land in its current state — either forested or agricultural use — or to convert the land to the other state. Relevant factors a landowner would be expected to consider include: typical agricultural revenues in the area (A_{it}); the quality of a specific land parcel for agricultural production (q_{ijt}); agricultural costs of production (M_{it}); typical forestry revenues (f_{it}); and the cost of converting land from a forested state to use as cropland (C_{it}). Thus, a risk-neutral landowner will seek to maximize the present discounted value of the stream of expected future returns:

$$\max_{\{g_{ijt},\, v_{ijt}\}} \int_0^\infty \Big[(A_{it} q_{ijt} - M_{it})(g_{ijt} - v_{ijt}) - C_{it}^{\alpha P_{it}} g_{ijt} + f_{it} S_{ijt} + W_{it} g_{ijt} - D_{it} v_{ijt} \Big] e^{-r_t t}\, dt \tag{1}$$

$$\textit{subject to:} \quad \dot{S}_{ijt} = v_{ijt} - g_{ijt} \tag{2}$$

[4] A detailed description of the dynamic optimization model and the derivation of the econometrically estimatable model is found in Stavins and Jaffe 1990. An illustration of the use of the model for environmental simulation is found in Stavins 1990.

[5] For the geographic area of the investigation — thirty-six counties along the Mississippi River in Arkansas, Louisiana, and Mississippi — it is empirically reasonable to focus on these two alternative land uses.

$$0 \leq g_{ijt} \leq \bar{g}_{ijt} \tag{3}$$

$$0 \leq v_{ijt} \leq \bar{v}_{ijt} \tag{4}$$

where i indexes counties, j indexes individual land parcels, and t indexes time; upper case letters are stocks or present values; and lowercase letters are flows.[6] The variables are:

A_{it} = discounted present value of the future stream of typical expected agricultural revenues per acre in county i and time t;
q_{ijt} = parcel-specific index of feasibility of agricultural production, including effects of soil quality and soil moisture;
g_{ijt} = acres of land converted from forested to agricultural use (deforestation);
v_{ijt} = acres of cropland returned to a forested condition (forestation);
M_{it} = expected cost of agricultural production per acre, expressed as the discounted present value of an infinite future stream;
C_{it} = average cost of conversion per acre;
P_{it} = the Palmer hydrological drought index and α is a parameter to be estimated, to allow precipitation and soil moisture to influence conversion costs;
f_{it} = expected annual net income from forestry per acre (annuity of stumpage value);
S_{ijt} = stock (acres) of forest;
r_t = real interest rate;
W_{it} = windfall of net revenue per acre from a one-time clear cut of forest (prior to conversion to agricultural use);
D_{it} = expected present discounted value of loss of income (when converting to forest) due to gradual regrowth of forest (first harvest of forest does not occur until the year $t + R$, where R is the exogenously determined rotation length);

[6] This specification implies that all prices and costs are exogenously determined in broader national or international markets, a reasonable assumption in the present application.

$\bar{g}_{ijt}$ = maximum feasible rate of deforestation; and
$\bar{v}_{ijt}$ = maximum feasible rate of forestation.

As is described in Appendix 1, application of control theoretic methods yields a pair of necessary conditions for changes in land use. Forestation (conversion of agricultural cropland to forest) occurs if a parcel is cropland and:

$$(\tilde{F}_{it} - A_{it} \bullet q_{ijt} + M_{it}) > 0 \tag{5}$$

where$_{it}$, delayed net forest revenue, equals F_{it} - D_{it}, and $F_{it} = f_{it}/r_t$. That is, a parcel of cropland should be converted to forestry use if the present value of expected net forest revenue exceeds the present value of expected net agricultural revenue. On the other hand, deforestation occurs if a parcel is forested and:

$$(A_{it} \bullet q_{ijt} - M_{it} - C_{it}^{\alpha p_{it}} - FN_{it}) > 0 \tag{6}$$

where FN_{it}, net forest revenue, equals F_{it} - W_{it}. That is, a forested parcel should be converted to cropland if the present value of expected net agricultural revenue exceeds the present value of expected net forest revenue plus the cost of conversion.

Inequalities (5) and (6) imply that all land in a county (of given quality) will be in the same use in the steady state. In reality, of course, counties are observed to be a mix of forest and farmland. Although this may partly reflect deviations from the steady state, it is due largely to the *heterogeneity* of land, particularly in regard to its quality (suitability) for agriculture. Such unobserved heterogeneity can be parameterized within an econometrically estimatable model so that the *individual* necessary conditions for land-use changes (equations (5) and (6)) aggregate into a single-equation model, in which the parameters of the basic benefit-cost relationships and of the underlying, unobserved heterogeneity can be estimated simultaneously. In Appendix 2, the complete model is derived:

$$FORCH_{it} = FORCH_{it}^{a} \bullet D_{it}^{a} - FORCH_{it}^{c} \bullet D_{it}^{c} + \lambda_i + \phi_{it} \tag{7}$$

$$FORCH_{it}^{a} = \gamma_a \bullet \left[d_{it} \bullet \left[F \left[\frac{log(q_{it}^{y}) - \mu(1+\beta_2 E_{it})}{\sigma(1+\beta_3 E_{it})} \right] \right] + (1 - d_{it}) - \left[\frac{S}{T} \right]_{i,t-1} \right] \tag{8}$$

$$FORCH_{it}^{c} = \gamma_c \bullet \left[d_{it} \bullet \left[1 - F \left[\frac{log(q_{it}^{x}) - \mu(1+\beta_2 E_{it})}{\sigma(1+\beta_3 E_{it})} \right] \right] + \left[\frac{S}{T} \right]_{i,t-1} - 1 \right] \tag{9}$$

$$d_{it} = \left[\frac{1}{1 + e^{-(N_i + \beta_1 E_{it})}} \right] \tag{10}$$

$$q_{it}^{y} = \left[\frac{\tilde{F}_{it} + M_{it}}{A_{it}} \right] \tag{11}$$

$$q_{it}^{x} = \left[\frac{FN_{it} + M_{it}}{A_{it} - C_{it}^{\alpha P_{it}}} \right] \tag{12}$$

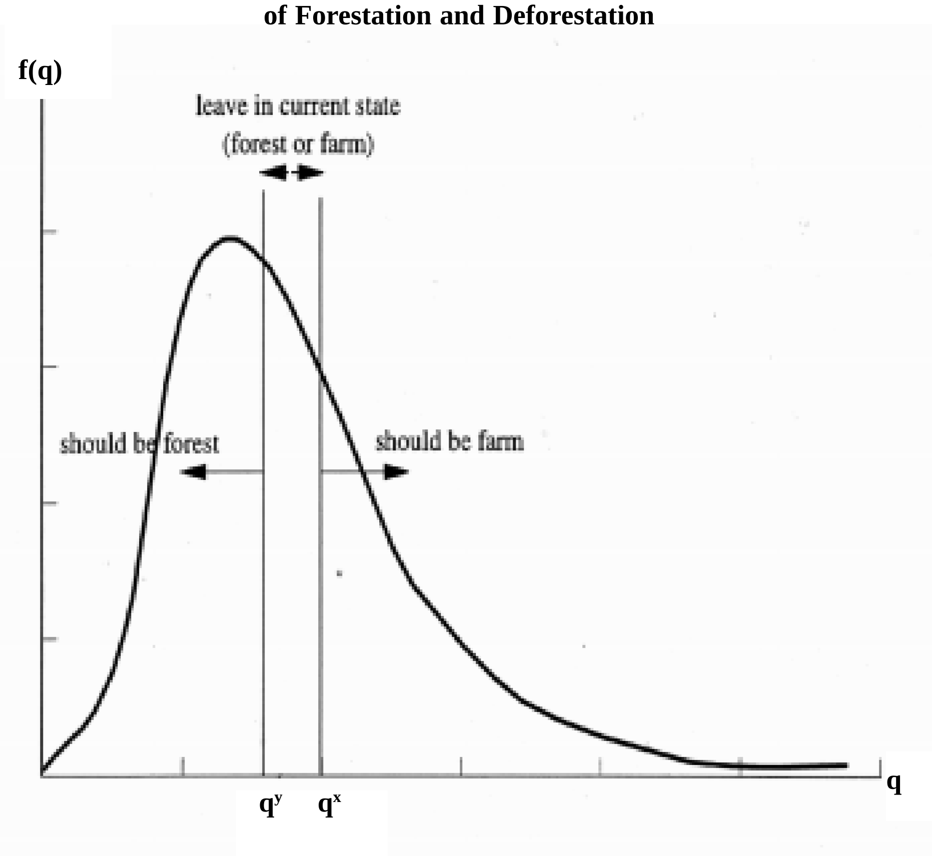
where all Greek letters are parameters that can be estimated econometrically; $FORCH_{it}$ is the change in forest land as a share of total county area; $FORCH_{it}^{a}$ is forestation (abandonment of cropland) as a share of total county area; $FORCH_{it}^{c}$ is deforestation (conversion of forest) as a share of total county area; D_{it}^{a} and D_{it}^{c} are dummy variables for forestation and deforestation, respectively; λ_i is a county-level fixed-effect parameter; ϕ_{it} is an independent (but not necessarily homoscedastic) error term; γ_a and γ_c are partial adjustment coefficients[7] for forestation and deforestation; ***F*** signifies the cumulative, standard normal distribution function; q_{it}^{y} is the threshold value of (unobserved) land quality (suitability for agriculture) below which the incentive for forestation manifests itself; q_{it}^{x} is the threshold value of land quality above which the incentive for deforestation manifests itself; T_{it} is total county area; N_i is the share of a county that is naturally protected from periodic flooding; E_{it} is an index of the share of a county that has been artificially protected from flooding by Federal programs (by time t); μ is the mean of the unobserved land-quality distribution; and σ is the standard deviation of that distribution.[8]

A simplified, pictorial representation of the model is provided in Figure 1. The skewed distribution in the figure represents the parameterized lognormal distribution of unobserved land quality; and q_{it}^{y} and q_{it}^{x} are the forestation and deforestation thresholds, respectively. Note that each is a (different) function of the benefits and costs of forest production relative to agricultural production. The asymmetries between equations (11) and (12) cause the separation between the two thresholds (where economic signals suggest to leave land in its existing state, whether that be forest or farm). Thus, if expected forest revenues increase, both thresholds shift to the right and we would anticipate that some quantity of farmland would be converted to forest uses. Likewise, an increase in expected agricultural prices means a shift of the two thresholds to the left, and consequent deforestation.

[7] Conditions (5) and (6) imply that conversion of land to its optimal use (conditional upon prices) will be instantaneous. As suggested above, there are several reasons why this may not be the case, including liquidity constraints, uncertainty about the permanence of price movements, decision-making inertia, and an uneven forest-age distribution. The partial adjustment mechanism allows for gradual movement toward the optimal state. Given the aggregate nature of the analysis, the coefficients indicate the probability that a landowner not in equilibrium in a given time period will switch to the optimal use within the initial time period.

[8] Other parameters to be estimated are: α, the effect of weather on conversion costs; β_1, the effect of government flood-control programs on agricultural feasibility; β_2, the effect of these programs on the heterogeneity mean; and β_3, the effect of programs on the standard deviation.

Figure 1. The Distribution of Land Quality and Economic Thresholds of Forestation and Deforestation



Using panel data for 36 counties in Arkansas, Louisiana, and Mississippi, during the period 1935-1984, the parameters of the model embodied in equations (7) through (12), above, were estimated with nonlinear least squares procedures (Stavins and Jaffe 1990). The basic results are found in Table 1.[9]

[9] The time dimension of the panel has observations every five years; hence, the time series contains ten periods, and the entire panel contains 360 observations. Estimated parameters are all of the expected sign, and nearly all estimates are significant at the 90, 95, or 99 percent level. Both parameter and standard error estimates are robust with respect to modifications of the specification, and the dynamic goodness-of-fit, based upon Theil's (1961) measure, is 0.675.

Table 1. Parameter Estimates for Simulations[a]

Parameter	Interpretation	Estimate
γ_a	Forestation partial adjustment	0.36717[b] (0.184)[c]
γ_c	Deforestation partial adjustment	0.64826 (0.154)
μ	Mean of unobserved quality distribution	1.11650 (0.364)
σ	Standard deviation of unobserved quality distribution	0.43848 (0.067)
α	Weather impact on conversion cost	1.59720 (0.304)
β_1	Federal program impact on agricultural feasibility	8.93700 (2.465)
β_2	Federal program impact on heterogeneity mean	0.77193 (0.774)
β_3	Federal program impact on heterogeneity standard deviation	0.42799 (0.183)
	Goodness of fit[d]	0.6747
	Log likelihood value	791.698
	Degrees of freedom	316

[a] For a detailed discussion of the parameter estimation, see: Stavins and Jaffe 1990; and Stavins 1990.

[b] The model also contains 36 county dummy variables.

[c] Robust (heteroscedastic consistent) standard error estimates appear below parameter estimates.

[d] The dynamic goodness of fit statistic is equal to 1 – Theil's *U* statistic, based on comparing predicted and actual net rates of deforestation and forestation, at the county level, across time.

B. A Dynamic Simulation Model of Future Land Use

The initial step — conceptually — in moving from an estimated model of historical land use to a model of carbon sequestration involves introducing relevant silvicultural elements into the necessary conditions previously derived. There are three principal silvicultural dimensions to be considered: symmetries and asymmetries between forestation and deforestation; alternative species for forestation; and alternative management regimes.

First, it should be noted that equations (11) and (12) already exhibit two significant asymmetries between forestation and deforestation. Forestation produces a supply of timber (and hence, a forest-revenue stream) only with some delay, since the first harvest subsequent to establishment occurs at the completion of the first rotation, while deforestation involves an immediate, one-time revenue windfall from cutting of the stand, net of a loss of future revenues from continued forest production. Additionally, under actual management practices during the sample period of historical analysis, costs (C_{it}) were associated with converting forestland to agricultural cropland, but no costs were involved with essentially abandoning cropland and allowing it to return to a forested state. For the simulations associated with carbon sequestration policies, however, we also allow for the possibility of "tree farming," that is, intensive management of the forest, which brings with it significant costs of establishment.[10]

Second, there is the silvicultural dimension of choice of species. In the econometric analysis, only mixed stands[11] were considered to reflect historical

[10]Forest establishment costs include the costs of planting (purchase of seedlings, site preparation, and transplanting), post-planting treatments, and care required to ensure establishment (Moulton and Richards 1990). We adopt a value of $92/acre ($1990), based upon estimates by Richards, Moulton, and Birdsey (1993) for converted cropland in the Delta (three-state) region. Table 2 provides descriptive statistics of the major variables used in the simulation analysis.

[11]Mixed stands of appropriate shares of various species of hardwoods and softwoods, specific to each county and time period, were included in the data used for econometric estimation. The calculated revenue streams draw upon price data for both sawlogs and pulpwood in proportion to use, based upon 55-year rotations.

reality, but in the carbon-sequestration context it is important to consider the possibility of both mixed stands and tree farms (plantations of pure pine). We develop revenue streams for both, based upon observed practice in the region.[12]

The third silvicultural dimension is the choice of management regime. The historical analysis assumed that all forests were periodically harvested for their timber. For purposes of carbon sequestration, however, we should consider not only such conventional management regimes, but also the possibility of establishing «permanent stands» that are never harvested.[13] These three sets of silvicultural considerations lead to the following respecification of equation (11):

$$q_{its}^{y} = \left[\frac{\tilde{F}_{its} + M_{it} - K_{it}}{A_{it}} \right] \tag{13}$$

where F_{its} = delayed net forest revenue (F_{its} - D_{its}), now subscripted by *s* to indicate species (mixed stand or pine), and set equal to zero for the case of permanent (unharvested) stands; and

K_{it} = establishment costs associated with planting a pine-based tree farm.

Combining variable values associated with these silvicultural dimensions into logical sets yields four scenarios to be investigated (Table 3):[14] (1)

[12]The tree-farm revenue streams represent a mix of 80 percent loblolly pine and 20 percent slash pine, based upon practice in the area (Daniels 1994). A rotation length of 45 years is utilized, also reflecting standard practice (Moulton and Richards 1990).

[13]For permanent stands, no revenue from harvesting is generated, although establishment costs are still incurred for setting up plantations.

[14] In all four scenarios, the revenue associated with a decision to deforest, FN_{it}, is the present value of the one-time windfall from cutting at the time of deforestation minus the opportunity cost associated with the foregone stream of revenues from periodic cutting of an unmanaged mixed stand. This and all forest revenues are in the form of capitalized «stumpage values,» and hence are net of harvesting costs.

natural regrowth of a mixed stand, periodically harvested; (2) natural regrowth of a «permanent» mixed stand (no periodic harvest); (3) planting of a pine plantation, periodically harvested; and (4) planting of a permanent pine plantation.

As explained above, we have assumed that deforestation brings about not only a loss of future forest revenue, F_{it}, but also a one-time windfall of income, W_{it}, from the immediate sale of timber from the felled forest, the difference being net forest revenue, FN_{it}. In the context of carbon sequestration, it becomes important to allow for another possibility as well, namely that at the time of deforestation, merchantable timber is not sold, but simply burned along with all other on-site material. In this case, FN_{it} is replaced by F_{it} in equation (12), above (and equation (15), below).This alternative, which becomes quite important when we consider its carbon consequences, yields a set of four additional scenarios, numbered 5 through 8 in Table 3.

Next, we introduce some policy-inspired modifications to develop a forest supply function. First, note that dynamic simulations of fitted values of the model, employing current/expected values of all variables (including prices), will generate predictions of future forestation and/or deforestation (Stavins 1990). These results, aggregated across the 36 counties, constitute our baseline for policy analysis. Second, we can simulate what land-use changes would be forthcoming with changed values of specific variables. In general, we can examine the consequences of public policies that affect the economic incentives faced by landowners. The difference in forestation/deforestation between the first (baseline) and the second (counterfactual) simulation is the predicted impact of a given policy.

In order to generate a representation of the forest supply function, several types of policies can be considered. A payment (subsidy) could be offered for every acre of (agricultural) land that is newly forested. But this would provide an incentive for landowners to cut down existing forests simply to replant in a later year in exchange for the government payment. On the other hand, a tax could be levied on each acre of land that is deforested. But

Table 2. Descriptive Statistics[a]

Variable	Mean	Standard Deviation	Minimum	Maximum
Gross Agricultural Revenue ($/acre/year)	259.04	44.58	184.77	376.03
Agricultural Production Cost ($/acre/year)	220.39	52.03	143.61	359.81
Forest Revenue[b] ($/acre/year)				
Mixed Stand	19.29	7.45	6.71	38.36
Pine Stand	58.96	23.38	19.92	118.24
Tree-Farm Establishment Cost ($/acre)	92.00	0.00	92.00	92.00
Conversion Cost ($/acre)[c]	27.71	0.00	27.71	27.71
Fraction of County Naturally Protected from Periodic Flooding	0.614	0.264	0.177	1.000
Index of Artificial Flood Protection	0.371	0.371	0.000	1.418
Palmer Hydrological Drought Index	0.74	0.84	-1.05	1.69
Carbon Sequestration due to Forestation[d] (tons/acre)				
Natural Regrowth of Harvested Mixed Stand	43.36	0.00	43.36	43.36
Natural Regrowth of Permanent Mixed Stand	50.59	0.00	50.59	50.59
Pine Plantation Periodically Harvested	41.05	0.00	41.05	41.05
Pine Plantation, Permanent	49.99	0.00	49.99	49.99
Carbon Emissions due to Deforestation, with Sale of Merchantable Timber[e] (tons/acre)	51.83	0.00	51.83	51.83
Carbon Emissions due to Deforestation, with Burning of all Material (tons/acre)	72.64	0.00	72.64	72.64
Interest Rate[f]	5%	0.00	5%	5%

[a] The sample is of 36 counties in Arkansas, Louisiana, and Mississippi, located within the Lower Mississippi Alluvial Plain. All monetary amounts are in 1990 dollars; means are unweighted county averages.

[b] Gross forest revenue minus harvesting costs; an annuity of stumpage values.

[c] The historical analysis uses actual conversion costs, varying by year.

[d] Present value equivalent of life-cycle sequestration.

[e] Present value equivalent of life-cycle emissions.

[f] The historical analysis uses actual, real interest rates; simulations of future scenarios use the 5 percent real rate.

Table 3. Alternative Silvicultural Scenarios
Discount Rate = 5 Percent

Species Regime	Natural Regrowth of Mixed Stand				Pine Plantation			
Management Regime	Periodic Harvest		No Periodic Harvest		Periodic Harvest		No Periodic Harvest	
Deforestation Regime	Timber Sale[a]	Site Burn[b]	Timber Sale[a]	Site Burn[b]	Timber Sale[a]	Site Burn[b]	Timber Sale[a]	Site Burn[b]
Scenario Number	#1	#5	#2	#6	#3	#7	#4	#8
Deforestation Carbon Emissions[c] (tons/acre) Ω_t^E	51.83	72.64	51.83	72.64	51.83	72.64	51.83	72.64
Forestation Carbon Sequestration[c] (tons/acre) Ω_t^S	43.36		50.59		41.05		49.99	
Annual Forest Revenue ($/acre/year) f_{its}	19.29		0.00		58.96		0.00	
Establishment Costs ($/acre) K_{it}	0.00				92.00			

[a] If deforestation occurs, merchantable timber is sold; carbon thereby sequestered is partially and gradually released over time.

[b] If deforestation occurs, all on-site material is burned.

[c] Present value equivalent of life-cycle sequestration and emissions; see text for explanation.

such an approach would provide no added incentive for forestation of land that is not currently in that state. One solution is to think of a two-part policy that combines a subsidy on the flow of newly forested land with a tax on the flow of (new) deforestation. As a first approximation, the two price instruments can be set equal, although this is not necessarily most efficient.

We simulate this policy by treating the subsidy as an increment to forest revenues in the forestation part of the model (equation (8)) and treating the tax payment as an increment to conversion or production costs in the deforestation part of the model (equation (9)). Letting Z_{it} represent the subsidy and tax, the threshold equations ((11) and (12)) for forestation and deforestation, respectively, become:

$$q^{y}_{its} = \left[\frac{(\tilde{F}_{its} + Z_{it}) + M_{it} - K_{it}}{A_{it}} \right] \tag{14}$$

$$q^{x}_{its} = \left[\frac{FN_{its} + (M_{it} + Z_{it})}{A_{it} - C_{it}^{\alpha P_{it}}} \right] \tag{15}$$

Thus, a dynamic simulation, based upon equations (7), (8), (9), (10), (14), and (15), in which the variable Z is set equal to zero, will generate a baseline quantity of forestation/deforestation over a given time period.[15] By carrying

[15] The simulated (fitted) values from the model are the set of values that make up the vector $FORCH_{it}$ for any time t in equation (7). Multiplying these predicted values of $FORCH_{it}$ by county land areas, T_i, and adding these products to the elements of the vector $S_{i,t-1}$ yields predicted values of S_{it}, which are in turn fed back into the simulation for the following time period via the term $[S/T]_{i,t-1}$ in equations (8) and (9). The simulation process is actually a two-stage procedure for each time period, in which the values of the dummy variables, D_{it}^{a} and D_{it}^{c} in equation (7), are first predicted on the basis of whether this same equation with both dummies set equal to unity yields a positive (forestation) or negative (deforestation) value; then the two dummy variables are adjusted accordingly and the vector $FORCH_{it}$ is simulated for that time period. This two-stage approach mirrors the econometric model that underlies the simulations (Stavins and Jaffe 1990).

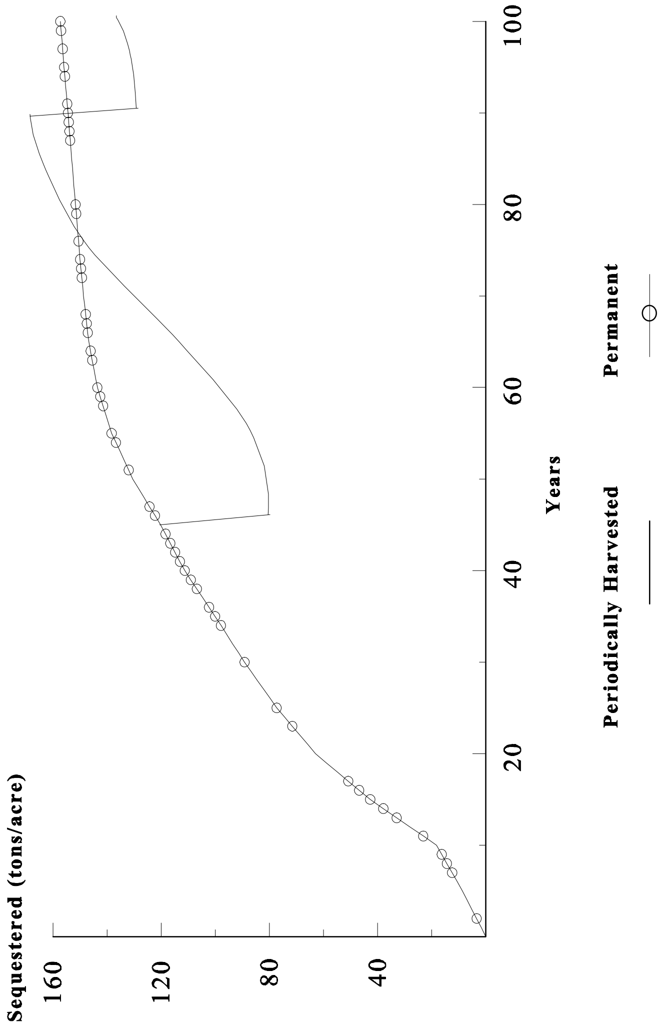
out simulations for various values of Z over the same time period, and subtracting the results of each from the baseline results, we can trace out a forest acreage supply function, with marginal cost per acre (Z) arrayed in a schedule with total change in acreage over the time period, relative to the baseline.

C. A Dynamic Simulation Model of Carbon Sequestration

For any given parcel of land, there are several types of comparisons that could be made between the time-paths of carbon emissions/sequestration in a baseline and a policy simulation (if relative prices are constant over time). First, we can consider a parcel that is continually in cropland in both simulations, in which case it exhibits zero net carbon sequestration/emission over the long run in both, and so the policy impact is also zero. Second, a parcel may continually be in a forested state in both simulations, in which case it sequesters carbon in both simulations (*if* it is periodically harvested, since atmospheric carbon is converted to wood products), but net sequestration due to the policy intervention is again zero. Third, a parcel may continually be in agricultural use in the baseline, but forestation takes place in the policy simulation in year t. Here, the net carbon sequestration due to the policy intervention will be the time-path of (varying) *annual* sequestration (and, in some cases, emissions) that *commence* in year t. Fourth, a parcel may continually be in a forested state in the baseline, but deforestation takes place in the policy simulation in year t. Now, the net carbon *emissions* due to the policy intervention will be the time-path of (varying) *annual* emissions that *commence* in year t.

The next step, conceptually, is to link specific time paths of carbon sequestration (and emissions) with the various types of forestation and deforestation specified. Scientific understanding of these linkages is continually evolving; we base our modeling of the relationships upon state-of-the-art biological models. Figure 2 provides a pictorial representation of one example of the biological time path of carbon sequestration and emission

Figure 2. Time Profile of Carbon Sequestration (Loblolly Pine in Delta States Region)



Source: Based on data from Moulton and Richards (1990) and Richards (1994).

linked with a specific forest management regime.[16] In the example depicted in the figure, the time profile is of cumulative carbon sequestration associated with establishing a *new* loblolly pine plantation in the study area. Carbon sequestration occurs in four components of the forest: trees, understory vegetation, forest floor, and soil (Birdsey 1992). When the plantation is managed as a permanent stand, cumulative sequestration increases monotonically, with the magnitude of annual increments declining so that an equilibrium quantity of sequestration is essentially reached within a hundred years, as material decay comes into balance with natural growth.

The figure also shows the cumulative carbon sequestration path for a similar stand that is periodically harvested (with 45-year rotations). In this case, carbon accrues at the same rate as in a permanent stand until the first harvest, when a substantial amount of carbon is released as a result of harvesting, processing, and manufacturing of derivative products.[17] Much of the carbon sequestered in wood products is also released to the atmosphere, although this

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[16]We employ a set of temporal carbon yield curves, as do Nordhaus (1991), and Richards, Moulton, and Birdsey (1993). Other sequestration cost studies have used point estimates of average flows.

[17]Although the shares vary greatly among forest types, reference points are: tree carbon contains about 80 percent of ecosystem carbon, soil carbon about 15 percent, forest litter 3 percent, and the understory 2 percent. The variation in these shares is significant; for some species, soil carbon accounts for nearly 50% of total forest carbon. Our calculations of releases from the understory, forest floor, soil, and non-merchantable timber are based upon Moulton and Richards (1990) and Richards, Moulton, and Birdsey (1993). The share of total forest carbon that actually ends up in merchantable wood varies considerably. A reasonable reference point is about 40%. Much of the remaining 60% is released at the time of harvest and in the process of manufacturing wood products (in both cases through combustion), the major exception being soil carbon, which exhibits a much slower decay rate (reasonably assumed to be zero in some cases).

occurs with considerable delay as wood products decay.[18] As can be seen in the figure, in this scenario the forest is replanted, and the same process takes place again.

Although the carbon yield curve with harvesting in Figure 2 eventually moves above the yield curve for a «permanent» stand, this need not be case. It depends upon the share of carbon that is initially sequestered in wood products and upon those products' decay rates (plus the decay rate of soil carbon). With zero decay rates, the peaks in the harvesting yield curve would increase monotonically, but with positive decay rates, the locus of the peaks approaches a steady-state quantity of sequestration, and that quantity can, in theory, lie above or below the level associated with the equilibrium level of the «permanent» yield curve.

Recognizing the intertemporal nature of net carbon sequestration raises a question: how can we associate a number — the marginal cost of carbon sequestration — with diverse units of carbon that are sequestered in different years over long time horizons? This becomes particularly important if we wish to compare the costs of carbon sequestration with the costs of conventional carbon abatement measures, such as fuel switching and energy-efficiency enhancements. Previous sequestration studies have used a variety of methods to calculate costs in terms of dollars per ton, the desired units for

[18] As Sedjo, Wisniewski, Sample, and Kinsman (1995) point out, examinations of the long-term effects of timber growth on carbon sequestration are «highly dependent upon the assumptions of the life-cycle of the wood products» (p. 23). Harmon, Farrell, and Franklin (1990) found this to be the case in their scientific review. The two critical parameters are the assumed length of the life-cycle of wood products, and the assumed share of timber biomass that goes into long-lived wood products. Drawing upon the work of Row (1992), Row and Phelps (1990), and Turner *et. al.* (1993), we develop a time path of gradual decay of wood products over time, based upon an appropriately weighted average of pulpwood, sawlog, hardwood, and softwood estimates from Plantinga and Birdsey (1993). The final profile is such that one year following harvest, 83 percent of the carbon in wood products remains sequestered; this percentage falls to 76 percent after 10 years, and 25 percent after 100 years (and is assumed to be constant thereafter). At an interest rate of 5 percent, the present value equivalent sequestration is approximately 75 percent, identical to that assumed by Nordhaus (1991).

a cost-effectiveness comparison. These approaches have been classified as: flow summation, mean-carbon storage, and levelization. Each has limitations.

The first approach is the simplest: the present value of costs is divided by the total tons of carbon sequestered, regardless of when sequestration occurs. This summary statistic has several obvious problems associated with it: first, it fails to take into account the time profile of sequestration; and second, the measure is very sensitive to the length of the time horizon selected for calculation (in the case of periodic-harvesting scenarios). Furthermore, assuming that not only costs but also benefits of sequestration are to be discounted over time, this approach implies that marginal benefits of sequestration are increasing exponentially over time at the discount rate. A similar summary statistic is based upon mean carbon storage. In this case, the present value of costs is divided by the numerical average of annual carbon storage. This statistic suffers from the same problems as the first.

The third alternative summary statistic seems most reasonable, and is utilized here: the discounted present value of costs is divided by the discounted present value of tons sequestered. This approach may be thought of as assuming that the marginal damages associated with additional units of atmospheric carbon are constant and that benefits (avoided damages) and costs are to be discounted at the same rate. Note that such an assumption of constant marginal benefits is approximately correct if marginal damages are essentially proportional to the rate of climate change, which many studies have asserted. We initially use a 5 percent rate, supplemented later by sensitivity analysis.

By developing the constituent intertemporal yield curves for various forest species,[19] location, and management conditions, we calculate a set of present-

[19] The yield curves provided in Figure 2 are simply examples for one species, loblolly pine. The growth curves that underlie respective yield curves are themselves a function, partly, of precipitation and temperature, both of which are presumably affected in the long run by atmospheric concentrations of CO_2 and induced climate change (Dixon, Brown, Houghton, Solomon, Trexler, and Wisniewski 1994). We ignore this endogeneity to climate change in estimating sequestration costs, as have all previous studies. Likewise, all studies have ignored potential economic endogeneity of relevant variables to climate change (Sohngen and Mendelsohn 1995).

value equivalent carbon-sequestration measures associated with: natural regrowth of a harvested mixed stand (43.36 tons); natural regrowth of a permanent mixed stand (50.59 tons); a pine plantation periodically harvested (41.05 tons); and a permanent pine plantation (49.99 tons). Additionally, we calculate present-value carbon emission measures for: deforestation with sale of merchantable timber (51.83 tons); and deforestation with burning of all on-site material (72.64 tons). These values are reported in Tables 2 and 3.

We define the present values (in year *t*) of the time-paths of carbon sequestration and carbon emissions associated with forestation or deforestation occurring in year *t* as Ω_t^S and Ω_t^E, respectively. Thus, the total, present-value equivalent net carbon sequestration/emissions associated with any baseline or policy simulation are calculated as:

$$PV(SEQ) = \sum_{i=1}^{36} \left[\sum_{t=0}^{90} (FORCH_{it}^{a} \bullet D_{it}^{a} \bullet \Omega_{t}^{S} - FORCH_{it}^{c} \bullet D_{it}^{c} \bullet \Omega_{t}^{E}) \bullet (1+r)^{-t} \right] \tag{16}$$

where

$$\Omega_t^S = \sum_{h=t}^{90} CS_h \bullet (1+r)^{t-h} \tag{17}$$

$$\Omega_t^E = \sum_{h=t}^{90} CE_h \bullet (1+r)^{t-h} \tag{18}$$

and where CS_h and CE_h are, respectively, annual incremental carbon sequestration and carbon emissions per acre under individual scenarios.

It might be argued that since the policy intervention we model is a tax/subsidy on land use, not on carbon emissions and sequestration, it does not lead to the true minimum carbon sequestration marginal cost function. This may seem to be a valid criticism in the narrowest analytic sense, but it is not valid in a realistic policy context. It would be virtually impossible to levy a tax on carbon emissions or a subsidy on sequestration, because the costs of administering such policy interventions would be prohibitive. Looked at this way, it becomes clear that such an instrument would likely be *more* costly per unit of carbon sequestered than would the deforestation tax/forestation subsidy policy considered here.

A simulation of equations (16), (17), and (18) with the subsidy/tax, Z, set equal to zero (in equations (14) and (15)) generates a baseline quantity of carbon sequestration/emissions. By subtracting this quantity from the results of simulations employing positive values of Z, we trace out a supply curve of net carbon sequestration, in which the marginal costs of carbon sequestration, measured in dollars per ton, can be arrayed in a schedule with net annual[20] carbon sequestration.

III. Empirical Application

By way of example, Table 4 provides the results for a periodically harvested pine plantation, with the sale of merchantable timber when/if deforestation occurs.[21] Such a scenario is most directly comparable with those examined in other studies. The relatively attractive forest revenues associated with this management regime result in a small amount of net forestation taking place in the baseline simulation, a gain of about 52 thousand acres (over the 90-year study period). Baseline net carbon sequestration is approximately 4.6 million tons annually. Marginal costs of carbon sequestration increase gradually, until these costs are about $66 per ton,

[20]Recall that both dollars of costs and tons of sequestration (and emission) are discounted. Hence, annual sequestration refers to an annuity that is equivalent to a respective present value (employing a discount rate of 5 percent).

[21]For a detailed analysis of all eight scenarios and an examination of the sensitivity of carbon sequestration costs to changes in critical factors, see: Newell and Stavins 1998.

where annual sequestration relative to the baseline has reached about 7 million tons. This level of sequestration is associated with a land-use tax/subsidy of $100 per acre and net forestation, relative to baseline, of 4.7 million acres.

Beyond this point, marginal costs depart more rapidly from a linear trend. Beyond about $200 per ton, they turn steeply upward (Figure 3).[22] Indeed, the marginal cost function is nearly asymptotic to a sequestration level of about 15 to 16 million tons annually. This is not surprising, since such an implicit limit would be associated with net forestation of about 10.5 million acres, for a total forested area of 13 million acres, just shy of the total area of the study region.

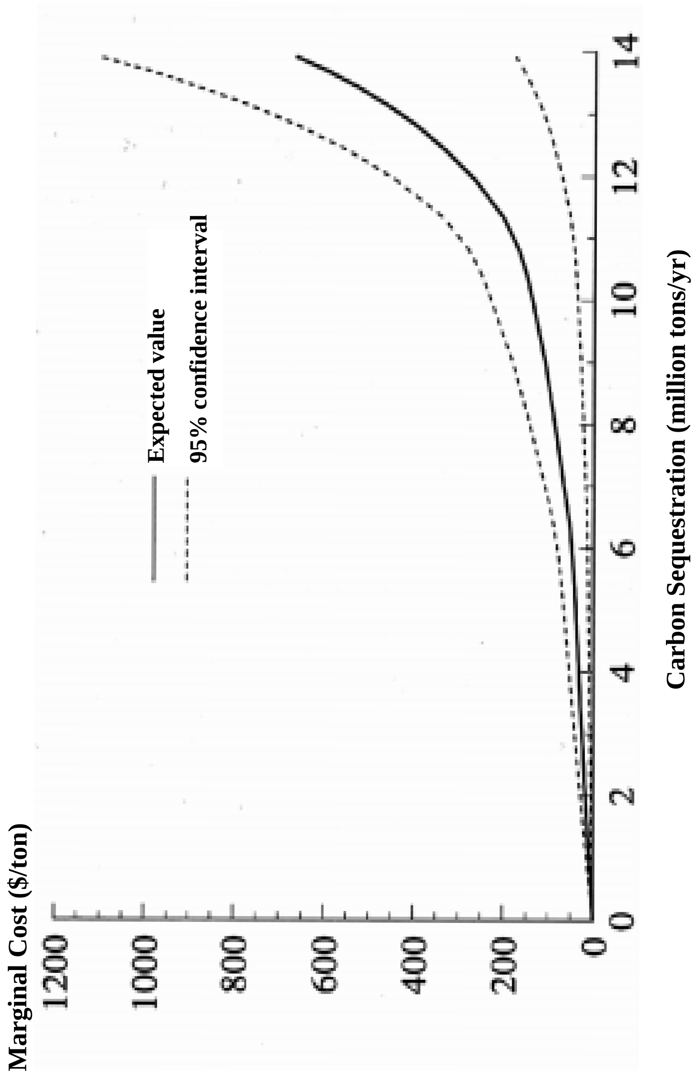
Because of variations in methodology and differences in geographic area of analysis, it is difficult to make direct comparisons of results among carbon-sequestration studies. Most studies have not even reported marginal cost functions; instead the vast majority have simply provided a single point estimate of average sequestration costs at some level of total sequestration. If marginal costs are increasing, indeed steeply increasing after some point, as the present study suggests, then such single point estimates of average costs are of only very limited use. Indeed, they can be misleading if improperly applied.

In Table 5, we have summarized the results of some of the best and most comparable studies of carbon sequestration. Six of the nine studies provide estimates of a marginal cost function. We summarize the results in the table along three dimensions: total quantity (of land affected and carbon sequestered), average cost, and marginal cost.

The most direct comparison that can be made is with the work of Richards, Moulton, and Birdsey (1993), who used an engineering approach to develop estimates for the Delta states (of Arkansas, Louisiana, and Mississippi). The comparison is of particular interest because many of the other dimensions of

[22]An additional advantage of the econometric approach to estimating the marginal cost function is that error bounds can be established through stochastic simulations, drawing upon the estimated variance-covariance matrix.

Figure 3. Marginal Cost of Carbon Sequestration
(Scenario 3. Periodically Rarvested Pine Plantation)



Source: Based on data from Moulton and Richards (1990) and Richards (1994)

Figure 4. Alternative Estimates of Marginal Cost of U.S. Carbon Sequestration

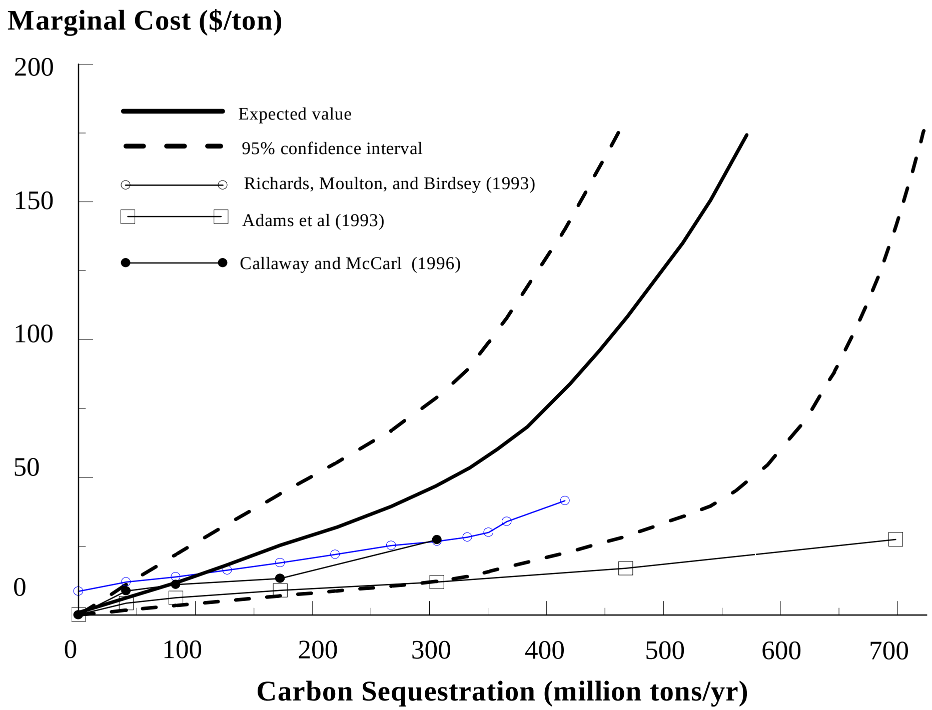


Table 4. Simulated Land Changes and Carbon Sequestration
Scenario #3: Periodically Harvested Pine Plantation, Sale of Merchantable Timber at Deforestation - Discount Rate = 5 Percent

Baseline Deforestation = + 51,654 acres   Baseline Carbon Sequestration = 4,578,202 tons

Marginal Cost per Acre ($/acre/yr)	Forestation Relative to Baseline (1,000s acres)	Average Cost per Acre ($/acre/yr)	Annual Carbon Sequestration Relative to Baseline (1,000s tons/yr)	Marginal Cost of Carbon Sequestration ($/ton)	Average Cost of Carbon Sequestration ($/ton)
0	0	0.00	0	0.00	0.00
10	518	10.00	784	6.61	6.61
20	1,057	15.10	1,600	13.21	9.97
30	1,615	20.25	2,445	19.82	13.38
40	2,192	5.45	3,319	26.42	16.81
50	2,787	30.69	4,219	33.03	20.27
60	3,398	35.96	5,145	39.63	23.76
70	3,893	41.27	5,895	46.24	27.26
80	4,224	46.60	6,395	52.84	30.78
90	4,455	51.95	6,745	59.45	34.31
100	4,653	57.32	7,045	66.05	37.86
200	6,579	105.63	9,961	135.97	69.77
300	7,484	129.15	11,332	202.03	85.31
400	7,897	142.25	11,957	268.05	93.96
500	8,212	155.98	12,434	334.11	103.03
600	8,470	169.22	12,825	400.18	111.77
700	8,689	182.74	13,156	466.22	120.71
800	8,874	195.72	13,437	532.20	129.28
900	9,038	208.21	13,685	598.31	137.53
1000	9,178	219.53	13,897	664.35	145.01

the analyses are quite similar. Since the present study focuses on just 36 counties in the Delta states, however, it is possible to compare the results only by extrapolating from the study area to the larger tri-state region. The marginal cost function that is thereby developed[23] is much steeper than that of Richards, Moulton, and Birdsey (1993), and lies below it up to about 30 million tons of carbon sequestration (marginal cost of about $22).

So that we can directly compare the results from our own and other studies, we need to normalize the results to some common set of standards. Since the other studies of carbon sequestration costs (and carbon abatement costs, as discussed later) are for the U.S. as a whole, one thing we need to do is normalize our results for the U.S. In doing so, it is important to recognize that the marginal costs of sequestration in the Delta states are not necessarily representative of nationwide sequestration costs.[24] The purpose of the normalization is to provide a basis for comparison of study results. The purpose is not to provide definitive cost estimates for the entire U.S. on the basis of a regional econometric analysis.

First, we can scale up the horizontal dimension from Figure 3 to represent the change from the study area to the relevant U.S. land base.[25] Second, we

[23]The 36 counties in the study area represent 13.34 percent of the total area of the three states. If the study area were perfectly representative of the total area, we could multiply our quantity results by 7.5 to compare with the three-state results of Richards. Of course, the study area is not truly representative of the total three-state area along all relevant dimensions. For one thing, it contains better quality (for agriculture) land. On the other hand, there are large areas of government owned lands outside the 36 counties; these would be unaffected by economic signals. These factors work in opposite directions. We use the multiplier of 7.5 simply for the purpose of demonstrating how the results may be related to those of others.

[24]It is likely that the difference is not very great. During the relevant time period, farm real estate prices in Arkansas, Louisiana, and Mississippi have tended to be about 15 to 20 percent greater than the U.S. average. Hence, opportunity costs of carbon sequestration are somewhat higher in the Delta states, and the actual U.S. marginal cost function probably lies somewhat below the function portrayed in Figure 4, but not significantly so.

[25]The scaling factor is equal to the ratio of total farm acreage in the continental U.S. (551 million acres in Richards, Moulton, and Birdsey 1993) to total farm acreage in our 36 study counties (10.6 million acres). It is agricultural acreage alone that is relevant for the normalization because in the scenario considered (#3) there is no deforestation in the baseline (and hence all carbon sequestration is coming from planting trees on formerly agricultural land).

Table 5. Comparison with results from other studies

Study	Total Quantity		Average Cost		Marginal Cost	
	Land (mil. acres)	Carbon (mil. tons/yr)	Land ($/acre/yr)	Carbon ($/ton)	Land ($/acre/yr)	Carbon ($/ton)
This Study[a]						
United States normalization	342	518	106	70	< 200	< 136
Delta States	5	7	58	8	< 100	< 66
Moulton and Richards (1990)						
United States[b]	269	690	–	27	< 81	< 37
Delta States Cropland	25	67	50	22	–	..
Richards, Moulton, and Birdsey (1993)						
United States[c]	244	416	–	–	–	< 41
Delta States Cropland[d]	11	29	42	18	< 52	< 22
Adams, et al. (1993)[e]	274	700	–	–	–	< 27
Nordhaus (1991)[f]	248	44	81	64	–	–
Parks and Hardie (1995)[g]	9	22	49	21	–	< 24
Rubin et al. (1992)[h]	71	73	–	23	–	–
Dudek and LeBlanc (1990)[i]	14	–	–	39	–	–
Plantinga (1995)[j]	0.65	1.5	–	–	–	6-13
Callaway and McCarl (1996)[k]	187	280	–	–	–	< 25

[a] From Scenario 3, pine plantation, periodically harvested, at a 5% discount rate.
[b] Permanent stands on cropland and pastureland only, i.e., not forest land.
[c] Figure for total U.S. carbon sequestration is an annuity calculated at 5% over 160 years.
[d] These figures were used, but not reported, in Richards, Moulton, and Birdsey (1993). Reference is to a permanent pine stand, based on data provided in a personal communication from Richards (1994). Carbon costs and tonnages were annualized over 160 years at a 5% discount rate.
[e] Nationwide results for a scenario with harvesting and sale of timber (Table 1, p. 79 and Table 4, p. 83), recalculated at a 5% discount rate.
[f] Permanent forestation of «marginal U.S. land» (Table 8, p. 60). For this and other studies, we have converted to acres at a rate of one hectare = 2.477 acres and to short tons at a rate of one metric ton = 1.102 short tons.
[g] Figures are for U.S. cropland-only scenario (Table 1, p. 127). Marginal costs were computed from marginal cost formula for Figure 4 (p. 131) using 22 million tons per year and annualized using a 4 percent discount rate over 10 years.
[h] Nationwide results converted from original study (Table 3, p 261) at a rate of 3.67 tons of carbon dioxide (CO_2) equals one ton of carbon, and into short tons from metric tons.
[i] An average permanent stand of U.S. tree species, from Table 3, p. 36; CO_2 converted to carbon.
[j] Figures are for a 14-county region of Wisconsin for the scenario assuming a least-cost program at a 4% discount rate and a constant annual sequestration rate of 2.25 tons of carbon per acre (Table II). Hectares converted to acres.
[k] Calculations use a 5% discount rate, employ carbon yield functions from Birdsey (1992), and do not allow for farm programs.

normalize the results from other studies by converting those results to appropriately discounted units. The results of this process are provided in Figure 4, where our own results are compared with those of Richards, Moulton, and Birdsey (1993), Adams, *et.al.* (1993), and Callaway and McCarl (1996). All of these alternative marginal cost functions lie within our 95 percent confidence interval, at least up to 300 million tons/year in the case of Adams, *et.al.* (1993), but all are less steep than our central tendency and lie well below it for most of their ranges. Overall, the general impression from this study is that the marginal costs of carbon sequestration are at least as great and may well be greater than previously reported.[26]

Returning to Table 5, we can also calculate the net carbon sequestration per acre implied by the various analyses. The figure for the Delta states from Richards, Moulton and Birdsey (1993) is 2.64 tons per acre annually. Our implicit net sequestration for the equivalent management regime — Scenario 4, pine plantations with no periodic harvesting — is considerably less, 1.85 tons per acre annually. Since our carbon yield curves are closely related to those employed by Richards, Moulton, and Birdsey (1993), why does this significant difference exist?

The answer may provide some insight into potential advantages of the approach taken in this study. If the model of Richards, Moulton, and Birdsey (1993) were accurate in terms of its structural assumptions (and input data) that landowners behave "optimally" and immediately in response to economic signals and if our analysis were likewise correctly specified, then the marginal cost function simulated from our econometrically-based approach (and hence the implicit annual tons of carbon per acre) ought to be more or less the same as theirs. They are not. One possible explanation brings attention to a central advantage of an econometric approach: landowners do not necessarily

[26] Although these marginal costs are greater than the best independent estimates of the respective marginal costs of carbon abatement (through fuel switching and increased energy efficiency), the evidence indicates that carbon sequestration would be part, albeit a minority share, of a cost-effective portfolio of strategies in the United States, at least in the short run (Stavins 1998).

respond in the "optimal" and immediate fashion assumed in the engineering models. Indeed, the econometric evidence suggest that landowners have in the past responded to economic signals with considerable delay, particularly when shifting land use from agriculture to forestry. Thus, in our model a given tax/subsidy produces land-use changes, but not only may they be smaller than what is anticipated by Richards, Moulton, and Birdsey (1993) and others, but, more to the point, even if they are of the same magnitude in the steady state, our analysis suggests that those land-use responses will be drawn out over a considerable amount of time. In a world with discounting, this difference can be significant indeed.

IV. Implications for Future Research

Opportunities for future research are plentiful. The model developed here can be improved along a number of dimensions. Some improvements would represent not just marginal refinements of the current model, but rather improvements in the sense of a new and better model. Primary among these is endogenizing any one of a number of variables that are currently taken as exogenous: agricultural and forestry product prices; the mix of cultivated crops and forest species; and management regimes.[27] A general equilibrium approach should be possible, both at the econometric stage and in the simulations. This would not simply be desirable, but necessary, if the general approach developed here were to be applied directly to estimate the carbon sequestration marginal cost function for the United States as a whole.

Finally, we can comment briefly on the methodological implications of this work. The major advantage of our approach over the models that have

[27]It would be desirable to allow for the endogeneity of forest rotation length. Another approach to estimating the carbon supply function is found in a paper by Van Kooten, Binkley, and Delecourt (1995); they examine the sensitivity of the socially optimal rotation length to alternative values of carbon (dollars per ton), and thus develop a supply curve of carbon *per acre*. As timber prices increase, the optimal rotation length decreases; and as carbon value increases, the (socially) optimal rotation length increases.

dominated the literature on carbon sequestration is that simulations of marginal costs build directly upon revealed-preference patterns of how landowners have actually responded to the economic incentives they continually face regarding the alternative uses of their lands. This is in contrast with engineering approaches that build up marginal cost functions by aggregating point estimates of how landowners in a particular region or owning a particular type of land *ought* to behave, and in contrast with optimization models that often do much the same thing.

As is well known, landowners tend not to behave as they "ought" farmers, in particular, are notoriously sluggish in responding to some of the economic signals they face. For one thing, they are affected by non-pecuniary factors, including a desire to stay on the farm for reasons associated more with perceived quality of life than with financial returns. An econometric model based upon an underlying optimization model and allowing for "partial adjustment" or other phenomena can capture, albeit in a crude way, such land-use behavior. Hence, the land-use simulations that come from it, along with the respective estimates of carbon-sequestration costs may be better approximations of reality.

Linking a dynamic simulation model of carbon sequestration with an econometric model of land use has the potential of adding significantly to understanding of the costs of this frequently discussed approach to addressing the threat of global climate change. There is a growing literature of econometric analyses of forestation and deforestation (Panayotou and Sungsuwan 1989; Parks and Kramer 1995; Pfaff 1995; Reis and Guzmán 1992; and Southgate, Sierra, and Brown 1991). At least some of these can serve as the basis for revealed-preference analytical models of the respective marginal costs of carbon sequestration.

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Appendix 1. Solving the Dynamic Optimization Problem

Because of the linear nature of the objective function (equation (1) in the text), the optimal control turns out to have the usual "bang-bang" form. The solution, documented in greater detail in Stavins and Jaffe (1990) and Stavins (1990), proceeds as follows. First, the Hamiltonian equation, with ω_{it} as the costate variable, is:

$$H_{ijt} = \left[(A_{it}\, q_{ijt} - M_{it})(g_{ijt} - v_{ijt}) - C_{it}\, g_{ijt} + f_{it}\, S_{ijt} + W_{it}\, g_{ijt} - D_{it}\, v_{ijt}\right] e^{-r_t t} +$$

$$+ \omega_{ijt} \bullet \left[v_{ijt} - g_{ijt}\right] e^{-r_t t} \qquad \text{(A 1)}$$

According to the maximum principle, the following complementary slackness conditions must hold:

$$g^*_{ijt} = \bar{g}_{ijt} \qquad if \;\; \frac{\partial H(\bullet)}{\partial g_{ijt}} > 0 \qquad g^*_{ijt} = 0 \;\; otherwise \qquad \text{(A 2)}$$

$$v^*_{ijt} = \bar{v}_{ijt} \qquad if \;\; \frac{\partial H(\bullet)}{\partial v_{ijt}} > 0 \qquad v^*_{ijt} = 0 \;\; otherwise \qquad \text{(A 3)}$$

An additional necessary condition for the maximization of equation (1) is:

$$\frac{\partial H(\bullet)}{\partial S_{ijt}} = - \frac{d}{dt}\left[\omega_{ijt} \bullet e^{-r_t t}\right] \qquad \text{(A 4)}$$

$$\omega_{ijt} = \frac{f_{it}}{r_t} + \frac{\dot{\omega}_{ijt}}{r_t} \qquad \text{(A 5)}$$

Evaluation of the partial derivatives in the first set of necessary conditions yields:

$$g^*_{ijt} = \bar{g}_{ijt} \quad if \quad \left[A_{it} q_{ijt} - M_{it} - C_{it} + W_{it} - \omega_{ijt} \right] > 0 \tag{A 6}$$

$$v^*_{ijt} = \bar{v}_{ijt} \quad if \quad \left\lfloor - A_{it} q_{ijt} + M_{it} - D_{it} + \omega_{ijt} \right\rfloor > 0 \tag{A 7}$$

Substituting from equation (5) into equation (6),

$$g^*_{ijt} = \bar{g}_{ijt} \quad if \quad \left[A_{it} q_{ijt} - M_{it} - C_{it} + W_{it} - \frac{f_{it}}{r_t} \right] > \frac{\omega_{ijt}}{r_t} \tag{A8}$$

If landowners have static expectations regarding all variables, the necess condition for *target* deforestation (conversion of forest to farm) reduces to:

$$g^*_{ijt} = \bar{g}_{ijt} \quad if \quad \left\lfloor A_{it} q_{ijt} - M_{it} - C_{it} + FN_{it} \right\rfloor > 0 \tag{A9}$$

$$g^*_{ijt} = 0 \quad otherwise$$

where FN_{it}, net forestry revenue, equals F_{it} - W_{it}, , and $F_{it} = f_{it}/r_t$.

Likewise, for forestation (conversion of farm to forest), equation (5) is substituted into equation (7), yielding the necessary condition for *targeted* forestation:

$$v^*_{ijt} = \bar{v}_{ijt} \quad if \quad \left[F_{it} - A_{it} q_{ijt} - M_{it} \right] > 0 \tag{A10}$$

$$v^*_{ijt} = 0 \text{ otherwise}$$

where F_{it}, delayed net forest revenue, equals F_{it} - D_{it}.

Equation (10) indicates that forestation should occur if a parcel is cropland and:

$$(\tilde{F}_{it} - A_{it} \bullet q_{ijt} + M_{it}) > 0 \tag{A11}$$

This is identical to condition (5) in the text. A parcel of cropland should converted to forestry use if the present value of expected net forest revenue exceeds the present value of expected net agricultural revenue. Likewise, equation (9) indicates that deforestation should occur if a parcel is forested and:

$$(A_{it} \bullet q_{ijt} - M_{it} - C_{it} - FN_{it}) > 0 \tag{A12}$$

This is identical to condition (6) in the text. A forested parcel should be converted to cropland if the present value of expected net agricultural revenue exceeds the present value of expected net forest revenue plus conversion costs.

Appendix 2. Aggregation of Necessary Conditions

Inequalities (5) and (6) in the text imply that all land (of given quality) in a county will be in the same use in the steady state. In reality, counties are observed to be a mix of forest and farmland. Although this may partly reflect deviations from the steady state, it is due largely to the *heterogeneity* of land, particularly in regard to its quality (suitability) for agriculture. Such heterogeneity can be characterized in terms of a probability density function, $\mathscr{F}\{q_{ijt}\}$, posited as a parametric lognormal relationship, because the general shape of that distribution is reasonable for a distribution of land quality:

$$\begin{aligned} &log(q_{ijt}) \sim N(\mu, \sigma^2) \quad with \quad probability\ d_{it} \\ &q_{ijt} = 0 \qquad with \quad probability\ (1 - d_{it}) \end{aligned} \tag{B1}$$

where μ and σ^2 are the mean and variance of the normal distribution, and d_{it} is the probability that agricultural production is feasible, such that:

$$d_{it} = \left[\frac{1}{1 + e^{-(N_i + \beta_1 E_{it})}} \right] \tag{B2}$$

where N_i is the share of a county that is naturally protected from periodic flooding; E_{it} is an index of the share of a county that has been artificially protected from flooding by Federal programs (by time t); and β_1 is a parameter that indicates the impact of artificial flood protection relative to the impact of natural flood protection. The logistic specification is used to constrain d_{it} to values between zero and unity, because empirical measures of N_i and E_{it} are only indexes of protection.

As described by Stavins (1990), a more general approach is to allow for the possibility that decisions by the government to protect land from flooding are not made independently from the land's relative potential for agricultural production. Thus, the underlying heterogeneity is itself affected by projects, and the parameters of the lognormal distribution, μ and σ^2, are themselves functions of E_{it}:

$$\log(q_{ijt}) \sim N\left[\mu(1+B_2 E_{it}),\ [\sigma(1+\beta_3 E_{it})]^2\right] \text{ with probability } d_{it} \tag{B3}$$

$$q_{ijt} = 0 \text{ with probability } (1 - d_{it})$$

Denoting the left-hand side of inequality (5) in the text by Y_{ijt}, we note there is an incentive to carry out forestation if $Y_{ijt} > 0$. Hence, there threshold value of land quality (q_{ijt}), denoted q_{it}^y, below which the incen for forestation manifests itself:

$$q_{it}^y = \left[\frac{\tilde{F}_{it} + M_{it}}{A_{it}}\right] \tag{B4}$$

Likewise, by denoting the left-hand side of inequality (6) in the text by X_{ijt}, we note that there is an incentive to carry out deforestation if $X_{ijt} > 0$. Therefore, there exists a threshold value of land quality (q_{ijt}), denoted q_{it}^x, above which the incentive for deforestation manifests itself:

$$q_{it}^x = \left[\frac{FN_{it} + M_{it}}{A_{it} - C_{it}^{\alpha P_{it}}}\right] \tag{B5}$$

Since there is an incentive to deforest parcel j (in county i at time t) if $q_{ijt} > q_{it}^x$, the (privately) optimal (the desired or target) stock of deforested land, expressed as a fraction of all land available is:

$$\left[\frac{AG}{T}\right]_{it}^{*} = \left[1 - \left(\frac{S}{T}\right)_{it}^{*}\right] = d_{it} \bullet \left[\int_{q_{it}^x}^{\infty} [\boldsymbol{F}_i\{s\}]\ ds\right] \tag{B6}$$

where $F_i[\cdot]$ is the lognormal density function. Therefore,

$$\left[\frac{AG}{T}\right]_{it}^{*} = d_{it} \bullet \left[1 - F_i\left[q_{it}^x\right]\right] \tag{B7}$$

where $F_i[.]$ is the cumulative lognormal distribution function, and

$$\left[\frac{AG}{T}\right]_{it}^{*} = d_{it} \cdot \left[1 - \boldsymbol{F}\left[\frac{\log(q_{it}^x) - \mu}{\sigma}\right]\right] \tag{B8}$$

where $\boldsymbol{F}[.]$ is the cumulative, standard normal distribution function.

There is an analogous equation for forestation, which gives the target stock of forested land as a fraction of the total available land:

$$\left[\frac{S}{T}\right]_{it}^{*} = d_{it} \cdot \left[\boldsymbol{F}\left[\frac{\log(q_{it}^y) - \mu}{\sigma}\right]\right] + \left[1 - d_{it}\right] \tag{B9}$$

where q_{it}^y is the threshold value of q_{ijt} below which the incentive for forestation manifests itself.

As described in detail by Stavins and Jaffe (1990), two specification issues must be addressed before the model embodied in equations (8) and (9), above, can be estimated: the possibility that adjustment toward optimal land use is not instantaneous; and combining the deforestation and forestation models into a single equation to be estimated.

As discussed in the text of the present paper, there are various reasons why land-use adjustment may not occur instantaneously. Hence, we allow for the possibility of partial adjustment in each observation period toward the optimal land-use pattern. In the case of deforestation, we have:

$$\left[\frac{AG}{T}\right]_{it} - \left[\frac{AG}{T}\right]_{i,t-1} = \gamma_c \bullet \left[\left[\frac{AG}{T}\right]^*_{it} - \left[\frac{AG}{T}\right]_{i,t-1}\right] + \varepsilon^c_{it} \qquad \text{(B10)}$$

where γ_c is the rate of partial adjustment and $\varepsilon_{it}^{\ c}$ is an error term composed of a county-specific (time-invariant) component, λ_i, and a component, $\phi_{it}^{\ c}$, which has mean zero, so that $\varepsilon_{it}^{\ c} = \lambda_i + \phi_{it}^{\ c}$. Likewise, in the case of forestation, we have:

$$\left[\frac{S}{T}\right]_{it} - \left[\frac{S}{T}\right]_{i,t-1} = \gamma_c \bullet \left[\left[\frac{S}{T}\right]^*_{it} - \left[\frac{S}{T}\right]_{i,t-1}\right] + \varepsilon^a_{it} \qquad \text{(B11)}$$

where γ_a is the rate of partial adjustment and $\varepsilon_{it}^{\ a}$ is an error term composed of a county-specific (time-invariant) component, λ_i, and a component, $\phi_{it}^{\ a}$, which has mean zero. Since county-level stocks of forested land and agricultural land are aggregates of individual decisions, these adjustment parameters represent the probability that a landowner not in equilibrium in a given time period will switch to the optimal land use within the initial period.[1]

[1] It might seem that a superior approach would be to incorporate adjustment costs or lags into the original optimization problem, but this cannot be done in a way which yields necessary conditions which can be aggregated across heterogeneous parcels to the county level. Any such mechanism must depend on deviations of individual parcels from optimality. Estimating a model with adjustment costs requires observing the relationship between the magnitude of deviations from equilibrium and the rate of movement. Since we do not observe individual parcels, this cannot be done, so any adjustment mechanism built into the individual model

Next, to combine equations (10) and (11) into one relationship, we define the net change in the forested fraction of the county between periods *t-1* and *t* as:

$$\left[\frac{\mathrm{AG}}{\mathrm{T}}\right]_{\mathrm{it}} - \left[\frac{\mathrm{AG}}{\mathrm{T}}\right]_{\mathrm{i,t-1}} = \left[\frac{\mathrm{S}}{\mathrm{T}}\right]_{\mathrm{i,t-1}} - \left[\frac{\mathrm{S}}{\mathrm{T}}\right]_{\mathrm{it}} = (-1) \bullet \mathrm{FORCH}_{\mathrm{it}} \qquad \text{(B12)}$$

Under the assumptions of the model, deforestation and forestation will never occur simultaneously in the same county, and so we can write:

$$FORCH_{it} = -D^{c}_{it}\gamma_{c}\left[\left[\frac{AG}{T}\right]^{*}_{it} - \left[\frac{AG}{T}\right]_{i,t-1}\right] + D^{a}_{it}\gamma_{a}\left[\left[\frac{S}{T}\right]^{*}_{it} - \left[\frac{S}{T}\right]_{i,t-1}\right] + \varepsilon_{it} \qquad \text{(B13)}$$

where D_{it}^{c} and D_{it}^{a} are dummy variables[2] for deforestation and forestation regimes; *[AG/T]** and *[S/T]** are the corresponding target stocks from equations (8) and (9), respectively; and ε_{it} is a composite error term, defined by:

$$\varepsilon_{it} = \varepsilon^{c}_{it} + \varepsilon^{a}_{it} = \lambda_{i} + \phi^{c}_{it} + \phi^{a}_{it} = \lambda_{i} + \phi_{it} \qquad \text{(B14)}$$

In the econometric estimation, the county-specific components of the error term, λ_i, are treated as fixed-effect parameters and the ϕ_{it} are assumed to be independently distributed across *i* and *t*, but not necessarily homoscedastic. Thus, equation (13) leads to a single-equation, fixed-effects model, the parameters of which can be estimated by nonlinear least squares with county dummy variables employed to eliminate any bias due to the county fixed effect. The final model is thus:

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could not be estimated with county data. One could specify a version of equation (1) with adjustment costs at the county level, but that would be equivalent to a representative-firm assumption. Thus, a fully dynamic optimal model can only be implemented with individual data.

[2] The dummy variables are endogenous. In the econometric estimation, the forestation and deforestation are first estimated separately to predict values for the dummy variables to be used when, in a second stage, equation (13) is estimated.

$$FORCH_{it} = FORCH^{a}_{it} \bullet D^{a}_{it} - FORCH^{c}_{it} \bullet D^{c}_{it} + \lambda_i + \phi_{it} \tag{B15}$$

$$FORCH^{c}_{it} = \gamma_c \bullet \left[d_{it} \bullet \left[1 - F \left[\frac{\log(q^{x}_{it}) - \mu(1 + \beta_2 E_{it})}{\sigma(1 + \beta_3 E_{it})} \right] \right] + \right. \tag{B16}$$

$$\left. + (1 - d_{it}) - \left[\frac{S}{T} \right]_{i,t-1} \right]$$

$$FORCH^{c}_{it} = \gamma_c \bullet \left[d_{it} \bullet \left[1 - F \left[\frac{\log(q^{x}_{it}) - \mu(1 + \beta_2 E_{it})}{\sigma(1 + \beta_3 E_{it})} \right] \right] + \left[\frac{S}{T} \right]_{i,t-1} - 1 \right] \tag{B17}$$

where d_{it}, q_{it}^{y}, and q_{it}^{x} are defined, respectively, by equations (2), (4), and (5), above. These six equations make up the complete econometric model and are reproduced in the main text as equations (7), (8), (9), (10), (11), and (12).